

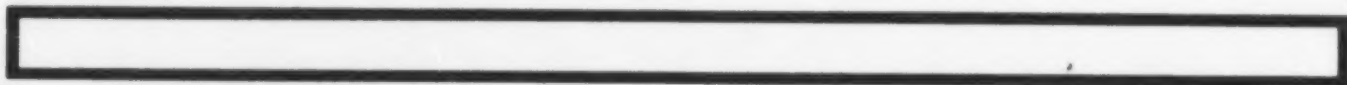
An Electrostatic Precipitator Backup
Filter for Sampling Systems

Southern Research Inst.
Birmingham, AL

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

8 Dec 80



U.S. Department of Commerce
National Technical Information Service

NTIS

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA-600/J-81-528	2. Journal Article	3. REC PB82-181926
4. TITLE AND SUBTITLE An Electrostatic Precipitator Backup Filter for Sampling Systems		5. REPORT DATE February 1982
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) P. Vann Bush, David H. Hussey, Duane H. Pontius, Wallace B. Smith (SRI, Birmingham, AL) and D. Bruce Harris (EPA/IERL-RTP)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southern Research Institute 2000 Ninth Avenue South Birmingham, AL 35205		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Journal Article; 1981
		14. SPONSORING AGENCY CODE EPA/600/13
15. SUPPLEMENTARY NOTES This is post-publication clearance, prior to submission to CERI (edited 1/23/80). Published in Atmospheric Environment, Vol. 15, No. 9, pp. 1675-1680, 1981.		
16. ABSTRACT An alternative technique for filtering the aerosol effluent from particle sampling systems has been developed. A two-stage electrostatic precipitation system was designed to collect with high efficiency the particulate material in a gas stream. The principal advantage of an electrostatic precipitator over conventional glass fiber backup filters is the ability to sample for long times without encountering filter pluggage or an excessive pressure differential across the system. Tests of a prototype electrostatic precipitator backup indicate collection efficiency for submicrometer diameter particles of 97 to greater than 99%.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS Pollution Electrostatic Precipitators Aerosols Dust Dust Filters	b. IDENTIFIERS/OPEN ENDED TERMS Pollution Control Stationary Sources Particulate	c. COSATI Field/Group 13B 13I 07D 11G 13K
REPRODUCED BY NATIONAL TECHNICAL INFORMATION SERVICE U.S. DEPARTMENT OF COMMERCE SPRINGFIELD, VA 22161		
19. DISTRIBUTION STATEMENT Release to Public	20. SECURITY CLASS (This page) Unclassified	21. NO. OF PAGES 6
	22. PRICE Unclassified	

AN ELECTROSTATIC PRECIPITATOR BACKUP FILTER FOR SAMPLING SYSTEMS

P. VANN BUSH,* DAVID H. HUSSEY, DUANE H. PONTIUS, WALLACE B. SMITH
Southern Research Institute, 2000 Ninth Avenue South, Birmingham, Alabama 35205, U.S.A.

and

D. BRUCE HARRIS

Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park,
North Carolina 27711, U.S.A.

(First received 9 October 1980 and in final form 8 December 1980)

Abstract—An alternative technique for filtering the aerosol effluent from particle sampling systems has been developed. A two-stage electrostatic precipitation system was designed to collect with high efficiency the particulate material in a gas stream. The principal advantage of an electrostatic precipitator over conventional glass fiber backup filters is the ability to sample for long times without encountering filter pluggage or an excessive pressure differential across the system. Tests of a prototype electrostatic precipitator backup indicate collection efficiency for submicrometer diameter particles of 97 to greater than 99%.

1. INTRODUCTION

Porous filters have historically been used to collect fine particles in particulate source sampling systems. However, problems are inherent in the use of filters. A large pump is usually required to pull the sample gas through a high efficiency filter, and many tests are terminated prematurely because of the large pressure drop that results as a 'cake' builds up on the filter. As an example, the sampling of flue gas having a particle loading which is comprised of predominately submicron diameter particles with a cyclone sampling system is often terminated by a blinding of the backup filter before a sufficient quantity of particulate matter to permit subsequent analyses is collected. Contamination of a sample with filter material or physical removal of the collected dust from the filter can also be problems. Glass fiber material may produce uncertainties in the weight of particulate collected due to gas phase reactions, as reported by Felix *et al.* (1977). All of these problems become more severe as the median diameter of the dust particles in the sample to be collected is reduced.

Particulate collection by electrostatic precipitation is an established technique which has none of the disadvantages of the porous filter. Electrostatic precipitators (ESPs) operate with a negligible pressure drop and are easily designed to have a high capacity for collected dust. However, ESPs used in lieu of a conventional filter on a sampling system may have unique problems. Electrical instability and poor collection due to back corona from high resistivity dust may be encountered. Poor performance due to a lack of particle adhesion may also result in some applications.

A theoretical prediction of the performance of an

ESP backup filter for sampling systems has been made. A prototype device was designed based on the theoretical study. Experiments were made to measure the electrical characteristics and the collection efficiency of the prototype.

2. THEORETICAL DEVELOPMENT

Design criteria

The design of the ESP backup filter has four primary requirements which had to be included in the theoretical evaluation of this electrostatic precipitator application. The device was to be operated at a nominal sample flowrate of $3 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$ at a temperature of 205°C. Collection of submicron particles with efficiency equivalent to that obtainable with glass fiber filters was required. A geometrical constraint was also imposed on the device; it was to be designed to pass through a sampling port 10 cm in diameter for in situ operation.

With these conditions considered, an electrode configuration for the ESP was selected. A cylindrical, two-stage geometry was employed. The first stage of the system primarily charges the particles. Efficient charging requires a high, near-uniform current density and a high electric field strength. The second stage of the system collects the precharged particles and thus must have a high, uniform electric field strength, but requires no current.

Figure 1 is a schematic diagram of the electrode geometry selected for study. The collector stage uses concentrically arranged collection electrodes to provide a large surface area in a relatively short length. Disc and needle corona discharge electrodes were considered for the charger stage.

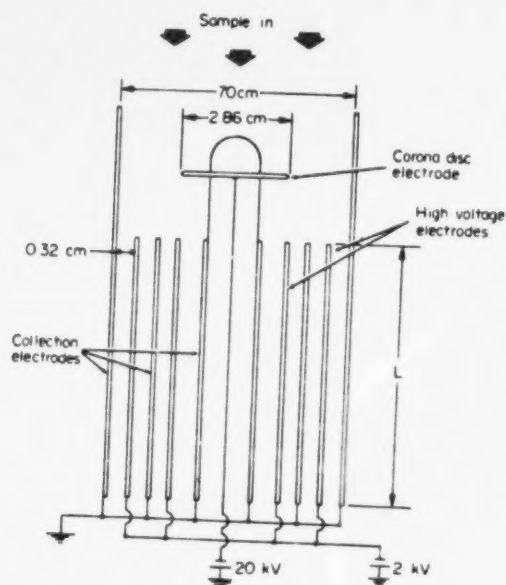


Fig. 1. Schematic of the ESP backup filter.

Performance evaluation

The disc-cylinder electrode design has been shown to be stable at very high values of corona current and electric field, and at high gas velocities by Klemperer and Sayers (1956) and Tassicker and Schwab (1977).

The electric field (neglecting space charge) in the disc-cylinder geometry can be derived in the following manner:

Consider the infinite plane $x = 0$, and the half-plane $y = 0$ bounded by the edge $x = d$, $y = 0$. Defining elliptic cylindrical coordinates ξ , η , z by

$$\left. \begin{aligned} x &= d \cosh \xi \cos \eta \\ y &= d \sinh \xi \sin \eta \\ z &= z \end{aligned} \right\} \quad (1)$$

then these two surfaces are $\eta = \pi/2$ and $\eta = 0$, respectively. If values of potential on these surfaces are set at $V(\xi, \pi/2, z) = 0$ and $V(\xi, 0, z) = V_0$, then the potential function is

$$V(\xi, \eta, z) = V_0 \left(1 - \frac{2\eta}{\pi} \right). \quad (2)$$

Now, using Equation (1), this equation is, in Cartesian co-ordinates

$$V(x, y, z) = V_0 - \frac{2}{\pi} V_0 \cos^{-1} \left\{ \frac{1}{d\sqrt{2}} \left[d^2 + x^2 + z^2 \pm \sqrt{(d^2 + x^2 + z^2)^2 - 4x^2d^2} \right]^{1/2} \right\}. \quad (3)$$

A conformal mapping may be performed to a disc-

cylinder geometry, after a change of variable $x = (\ln b) - x$. Then using

$$\bar{x} + iy = \ln r + i\theta,$$

the transformation is completed. The surface on which $V = 0$ becomes a cylinder of radius b . Defining $r = a$ as the boundary of the disc on which $V = V_0$, Equation (3) becomes

$$V(r, \theta, z) = V_0 - \frac{2}{\pi} V_0 \cos^{-1} \left\{ \frac{1}{\sqrt{2 \ln(b/a)}} \left[\ln^2(b/a) + \ln^2(b/r) + z^2 \pm \sqrt{(\ln^2(b/a) + \ln^2(b/r) + z^2)^2 - 4(\ln^2(b/a)(\ln^2(b/r)))} \right]^{1/2} \right\}. \quad (4)$$

The field may then be derived by taking the negative gradient of this expression. There is, of course, no dependence of V upon θ , since the geometry is cylindrically symmetric. In order to simplify the remainder of the development, consider the potential and the field only in the plane $z = 0$. Thus,

$$V(r, \theta, 0) = V_0 - \frac{2}{\pi} V_0 \cos^{-1} \left[\frac{\ln(b/r)}{\ln(b/a)} \right], \quad (5)$$

and the field $E(r)$ in the plane of the disc (radius a) is

$$E(r) = \frac{2V_0}{r\pi \ln(b/a)} \left[1 - \frac{\ln^2(b/r)}{\ln^2(b/a)} \right]^{-1/2}. \quad (6)$$

where V_a = applied voltage on the disc (V) (cylinder grounded); b = radius of the cylinder (m); and a = radius of the disc (m). The minimum value of the electric field in the plane of the disc occurs at $r = b$, where

$$E_{\min} = \frac{2V_a}{\pi b \ln(b/a)} \quad (7)$$

Using the values $b = 3.5 \times 10^{-2}$ m, $a = 1.43 \times 10^{-2}$ m, and $V = 16$ kV, we obtain $E_{\min} = 3.3 \times 10^5$ V m $^{-1}$.

Voltage-current characteristics for the disc-cylinder electrode geometry were measured to provide the projected operating data needed to continue the theoretical evaluation. The curves of current vs. voltage are shown in Fig. 2. At a temperature of 200 °C and 3.5×10^{-3} m ^{3} s $^{-1}$ flowrate the current, i , is approximately 200 μ A for an applied voltage of 16 kV. A current-controlled power supply is used with the system so the steepness of the V - I curve is not critical.

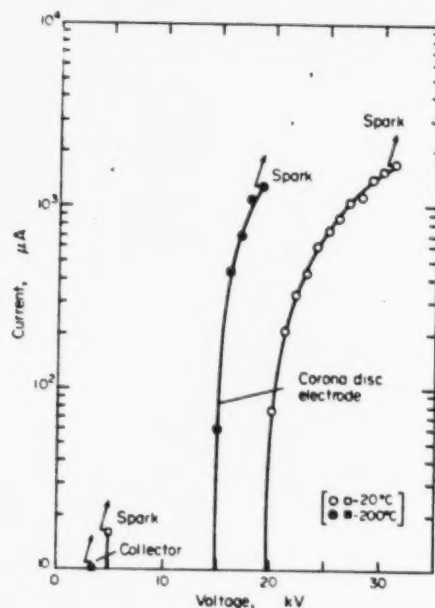


Fig. 2 Voltage-current characteristics of the ESP backup filter at two temperatures and a sampling rate of 3.5×10^{-3} m ^{3} s.

The ion concentration value, N , which is a determinant of the particle charging ability of the system can be determined from the equation

$$N = \frac{j}{e\beta E} \quad (8)$$

where j = current density = $i/2\pi bh$ (A m $^{-2}$); b = radius of the cylinder (m); h = width of the charging region on the cylinder wall (m); e = electronic charge (C); β = ion mobility (m ^{2} V $^{-1}$ s $^{-1}$); and E = electric field strength (V m $^{-1}$). The average time of residence in

the charging region is approximately equal to

$$t = \frac{h}{v} \quad (9)$$

where v = average gas velocity (m s $^{-1}$).

Thus the ion concentration-time product necessary for calculating particle charge is derived from the combined form of Equations (8) and (9):

$$Nt = \frac{i}{2\pi be\beta E v} \quad (10)$$

According to Loeb (1965) a typical value of ion mobility for either positive or negative corona in air at room temperature is 2.2×10^{-4} m ^{2} V $^{-1}$ s $^{-1}$. The mobility at 200 °C would possibly be as high as 5×10^{-4} m ^{2} V $^{-1}$ s $^{-1}$. The average gas velocity, v , is given by

$$v = \frac{u}{A} \quad (11)$$

where u = gas volume flowrate (m ^{3} s); and A = annular area through which the gas passes (m ^{2}). With a gas volume flowrate of 3×10^{-3} m ^{3} s $^{-1}$ and using $A = 3.2 \times 10^{-3}$ m ^{2} we obtain the value $v = 9.6 \times 10^{-1}$ m s $^{-1}$. Thus, the ion concentration-time product is determined to be $Nt = 5.5 \times 10^{13}$ s m $^{-3}$.

There is sufficient definition of parameters to now calculate from theory (White, 1963) the average charge per particle in elementary units as a function of particle diameter. In order to conservatively estimate the performance of the ESP backup filter (as has been done in previous calculations by using the minimum electric field strength in the charger) the mobility of particles has been calculated. By selecting the particle diameter corresponding to the minimum mobility the minimum performance for the device can be predicted. The mobility M is determined from the equation

$$M = \frac{qC}{6\pi\alpha\mu} \quad (12)$$

where q = average charge per particle, (C), (from Field + Diffusion Charging equations); C = Cunningham slip correction factor; α = particle radius (m); and μ = viscosity of the medium (1.8×10^{-5} kg m $^{-1}$ s $^{-1}$).

A plot of mobility vs. particle diameter is shown in Fig. 3. The minimum mobility occurs at approximately 0.2 μ m dia. The average charge per particle of this size is calculated to be $q = 3.5 \times 10^{-18}$ C, where the particles are assumed to have a relative dielectric constant of 5.0 and are at a temperature of 200 °C. The mobility of the 0.2 μ m dia. particles is found to be $M = 1.9 \times 10^{-7}$ m ^{2} V $^{-1}$ s $^{-1}$.

The maximum distance a particle must travel before it reaches the collection electrode is just the collection plate separation, 0.32 cm (see Fig. 1). With the concentric cylinders closely spaced and with the given operating gas velocity, the flow through the collector stage is laminar (Reynolds number = 132). The collection efficiency of the ESP backup filter can therefore be calculated from the particle trajectory.

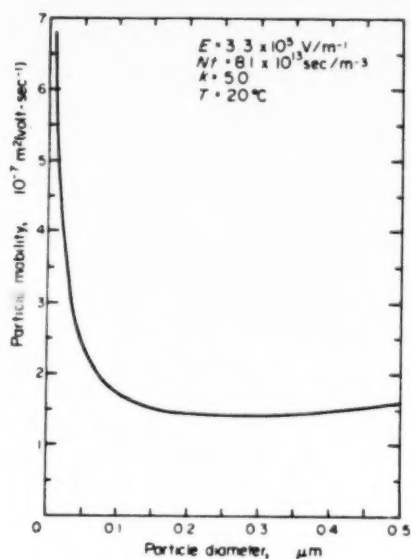


Fig. 3. Theoretical relationship between particle mobility vs particle diameter.

The actual velocity of the particles toward the collection plate is equal to the migration velocity, w , which is equal to the product of the electric field and the particle mobility. The velocity downstream through the collector is u/A_c , where u is the sample flowrate and A_c is the open cross-sectional area of the collector zone ($A_c = 3.2 \times 10^{-3} \text{ m}^2$).

The length of the collection plates required for 100% theoretical collection efficiency is given by

$$L = \frac{ud}{A_c w} \quad (13)$$

where d is the cylinder spacing ($3.2 \times 10^{-3} \text{ m}$). If we choose a value of $6.25 \times 10^5 \text{ V m}^{-1}$ for the collecting field (2 kV applied voltage) the migration velocity for the $0.2 \mu\text{m}$ dia. particles is $1.2 \times 10^{-1} \text{ m s}^{-1}$, and L is equal to 2.5 cm.

Having used the minimum electric field strength in the charger and the particle diameter giving the minimum mobility, the length of collection plates for 100% theoretical collection efficiency is a conservative specification for the requirements of the ESP backup filter.

3. EXPERIMENTAL VERIFICATION

A prototype ESP backup filter was designed and fabricated so that the performance could be experimentally evaluated. A collection plate length of 8.4 cm was used in the design and is more than three times the predicted length that is required. The prototype was fabricated from glass filled Teflon and type 316 stainless steel and has an overall length of 30 cm. Figure 4 is an assembly drawing of the ESP backup filter.

After a sample has been collected, the ESP is disassembled, immersed in a suitable liquid, and agitated ultrasonically. The wash can be filtered or evaporated to dryness, depending on the nature of the dust and the objectives of the test.

Laboratory aerosols

The experimental arrangement used to evaluate the ESP in preliminary laboratory tests is shown in Fig. 5. A log-normal aerosol of approximately $1 \mu\text{m}$ mass median diameter and geometric standard deviation of 2.0 was generated by nebulizing a 0.1% solution of fluorescein in 0.1N NH_3 . The aerosol was pumped

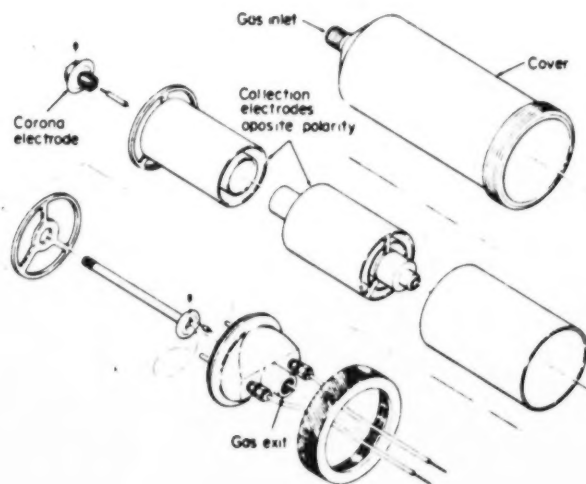


Fig. 4. Prototype ESP backup filter component arrangement.

through the ESP and the size dependent collection efficiency was determined by measuring the particle size distribution at the ESP outlet, with the power on and off, using a Thermosystems Model 3030 Electrical Aerosol Analyzer. The results of these experiments are summarized in Table 1. It is clear from the table that the ESP is capable of achieving the desired high collection efficiency for submicron particles.

Tests with flyash

Tests were conducted to determine the efficiency of the ESP backup filter when sampling redispersed flyash. The purpose of these tests was to investigate possible deleterious effects due to back corona and heavy dust loading.

Figure 6 illustrates the experimental setup for the flyash tests. A sample of flyash-laden air was with-

drawn from a duct downstream from a pilot scale precipitator. Flyash was injected into the heated gas stream with a sandblaster. The pilot precipitator was not energized, but acted as a settling chamber to effectively reduce the mass median diameter of the sampled particles without severely diminishing the number concentration of fine particles. The extracted sample passed through a heated probe, a cyclone, and into the ESP backup filter. A glass fiber filter was located downstream of the ESP to collect any ash that penetrated it, for determinations of the collection efficiency.

Two tests were run, each for 6 h, with a dust loading of 1.88 g m^{-3} at the pilot precipitator inlet. One test was run at 25°C , and the other at 170°C (where the flyash resistivity was below $10^{10} \Omega \text{cm}$ and approximately $5 \times 10^{11} \Omega \text{cm}$, respectively, as determined in

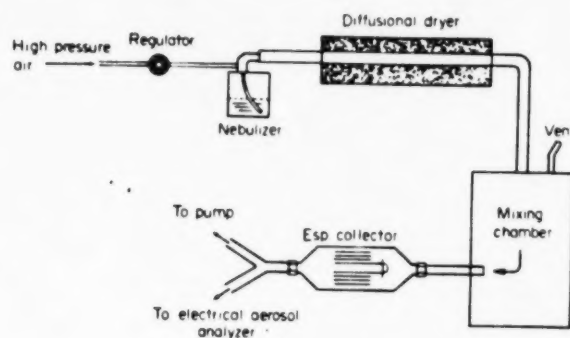


Fig. 5. Laboratory setup for evaluating the ESP backup filter.

Table 1. ESP backup filter laboratory performance

Particle size Flowrate (m^3/sec)	Collection efficiency (%)							
	0.0133	0.0237	0.0422	0.075	0.133	0.237	0.422	0.75
4.25×10^4	99.86	99.93	100.00	99.97	100.00	99.98	100.00	100.00
1.42×10^3		99.77	100.00	99.95	99.95	99.50	99.62	100.00
2.22×10^3	99.76	100.00	99.99	100.00	100.00	100.00	100.00	99.60
2.74×10^3	99.34	99.88	100.00	100.00	100.00	99.96	100.00	99.85

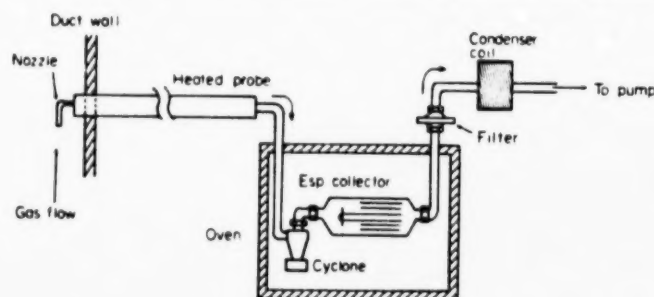


Fig. 6. Experimental setup for evaluating the ESP backup filter using redispersed flyash.

Table 2. Results of flyash tests with the ESP backup filter

	TEST 1	TEST 3
Corona voltage	22 kV	19 kV
Corona current	190 μ A	200 μ A
Collector voltage	2 kV	2 kV
Flowrate	$2.4 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$	$2.4 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$
Temperature	25 C	170 C
Sample time	6 h	6 h
Cyclone catch	40.0 g	(not measured)
ESP catch	0.016 g	0.017 g
ESP backup filter efficiency	96.3 %	97.6 %

the laboratory). After 6 h testing there was no noticeable increase in pressure drop across either of the filters. At each test's conclusion the ESP was disassembled, immersed in a beaker containing distilled water, and ultrasonically agitated. For these tests the resultant suspension was filtered, and the filters dried and weighed to determine the amount of particulate material collected.

The test conditions and results for the flyash experiments are presented in Table 2. Again, the ESP backup filter gave high collection efficiency: 96 and 98 % for the two tests, showing no evidence of degradation in performance by back corona with high resistivity dust loading.

4. SUMMARY AND CONCLUSIONS

The use of an electrostatic precipitator as a backup filter has been shown to be feasible. The prototype ESP backup filter produces the required high collection efficiency without the pressure drop which plagues porous filters in this application.

Since there is a potential for degraded performance when the ESP backup filter collects particles having a high resistivity, it is suggested that the ESP could be routinely run with a filter following it in the sampling train. If experience has shown the system to operate reliably at a particular source the porous filter can be eliminated. In any case, operation of sampling systems

without excessive pressure drop buildup and without forced, premature sampling termination can be achieved by using the ESP backup filter.

Acknowledgements—The assistance of K. Trowbridge in the design of the prototype device and R. Wilson and J. McCormack in performing the experiments is appreciated. A disc-cylinder electrode geometry and method similar to what is described in this paper have been developed by Air Pollution Systems, Inc., Kent, Washington, and the Electric Power Research Institute, Palo Alto, California for air pollution control. We have been advised by Air Pollution Systems, Inc., that U.S. and Foreign patents have been obtained and others applied for. We cannot ensure that practice of the system or method described in this paper does not infringe either said patents or any other private rights. The support of the U.S. Environmental Protection Agency for this work is gratefully acknowledged.

REFERENCES

- Felix L. G., Clinard G. L., Lacey G. E. and McCain J. D. (1977) Inertial cascade impactor substrate media for flue gas sampling. EPA-600/7-77-060, June, 1-2.
- Klemperer H. and Sayers J. E. (1956) Design aspects of an electrostatic precipitator for the collection of small solids ahead of the air heater. *Trans. ASME*, February, 317-326.
- Loeb L. B. (1965) *Electrical Coronas*, p. 451. Univ. California Press, Berkeley, California.
- Tassicker O. J. and Schwab J. (1977) High intensity ionizer for improved ESP performance. *J. Epr*, June/July, 56-61.
- White H. J. (1963) *Industrial Electrostatic Precipitation*, pp. 126-154. Addison-Wesley, New York.